

Deformable Mirror Technologies AOA Xinetics

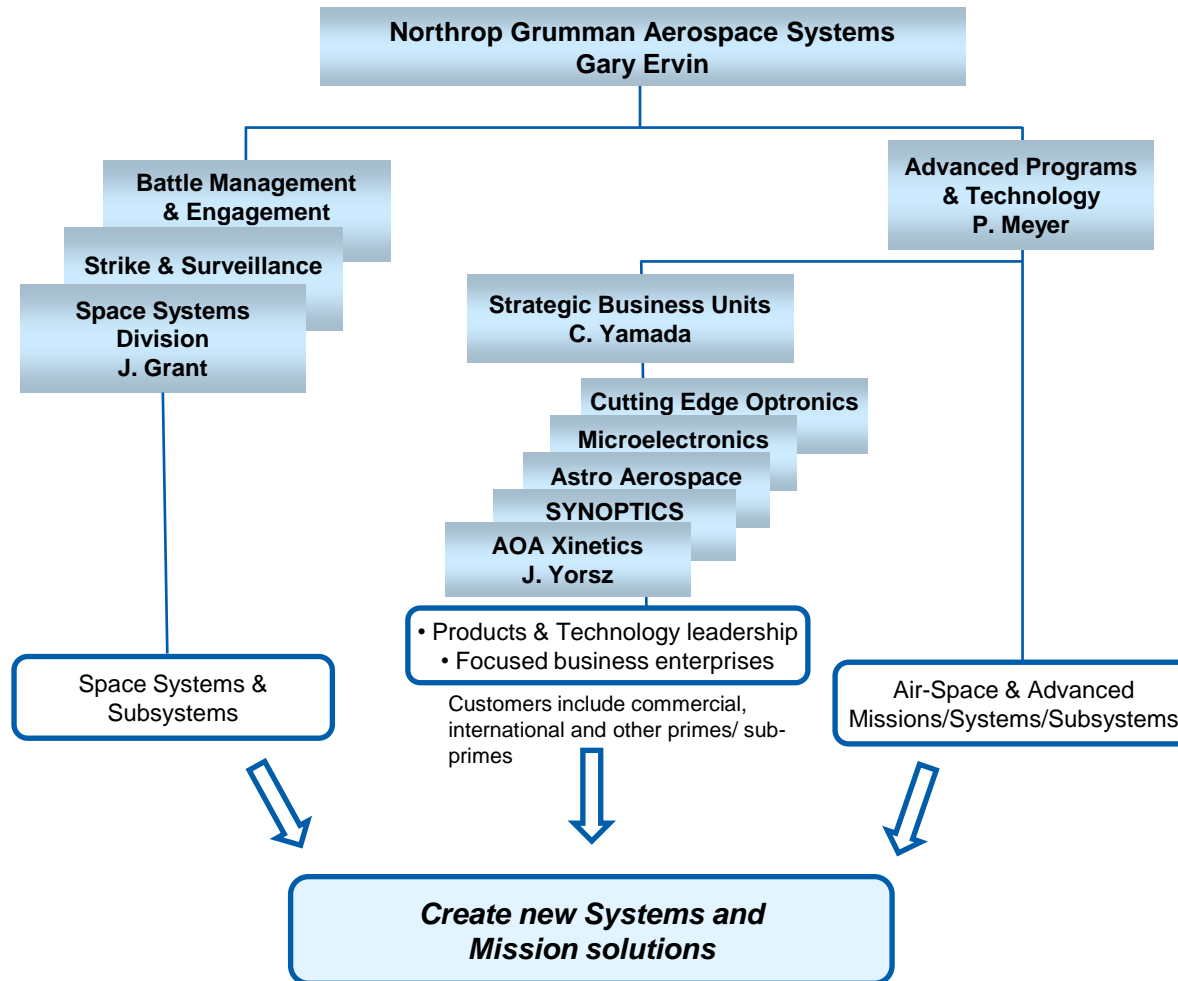
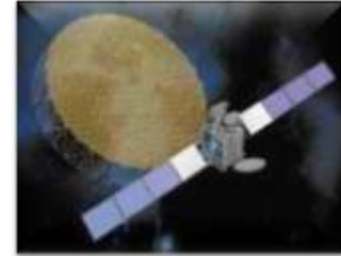
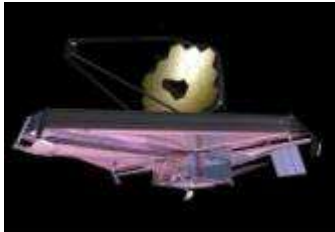


14 September, 2012

Dr. Allan Wirth
Chief Scientist, AOA Xinetics

Northrop Grumman Aerospace Systems Organization

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AOA Xinetics acquired to enable Advanced Optical Systems for Government and Commercial customers

Strategic Business Units (SBUs)



Adaptive Optics Associates / Xinetics (AOX) – Cambridge / Devens, MA

- Beam Control / Deformable Mirrors / Wavefront Sensors / Micro-Optics
- Precision SiC Optics/Structures
- EO Systems Development / Contract Manufacturing for Commercial and Government



Synoptics – Charlotte, NC

- Solid State Laser Materials / Components
- Advanced Crystal Growth
- Diverse Optical Manufacturing, Measurement, Engineering Support



Cutting Edge Optronics – St. Charles, MO

- Solid State Laser Materials / Components
- High Power Laser Diodes / Drivers
- Industrial / Military / Custom Laser Systems



Astro Aerospace – Carpinteria, CA

- Diverse array of products from reflectors to antennas to extendible and foldable structures
- Deployable Space Structures
- Systems Development / Manufacturing

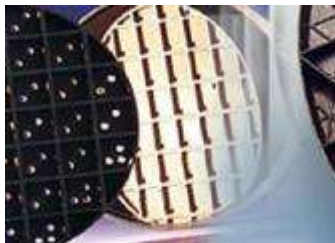


Microelectronics Products / Services – Redondo Beach, CA

- Family of Millimeter Wave Monolithic Integrated Circuits (MMICs)
- Commercial access to the Advanced Semiconductor Foundry
- Broad Range of Manufactured Products

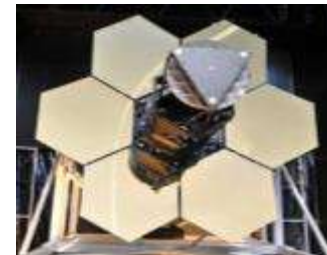
Adaptive Optic Associates / Xinetics (AOX) Business Areas

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Advanced Systems – Devens, MA

- Adaptive Optics for Space Imaging Systems
- Lightweight Precision Silicon Carbide Optics and Structures
- Nanolaminates
- Custom Design and Manufacturing



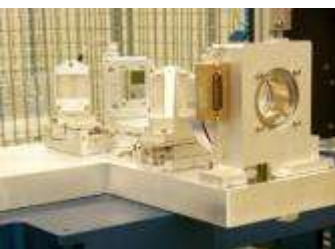
Intelligent Optics – Devens, MA

- Wavefront Sensing and Correction
- Beam Control Applications
- Deformable and Hybrid Mirror Design and Manufacturing
- Advanced Optical Applications



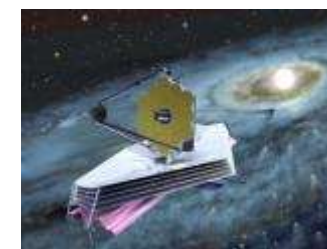
Systems and Services – Cambridge, MA

- Contract Optical and Software Development, Manufacturing, and Service
- Industrial Imaging Systems
- Scanning Systems / Laser Beam Delivery Systems
- Commercial and Government Applications



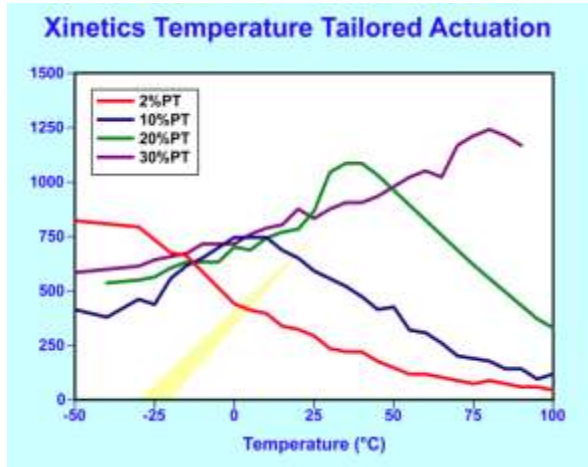
Special Programs – E. Hartford, CT

- Electro-Optical Systems Product Design, Manufacturing and Installation
- Production Cleanroom Facilities



Precision Motion with PMN Actuators

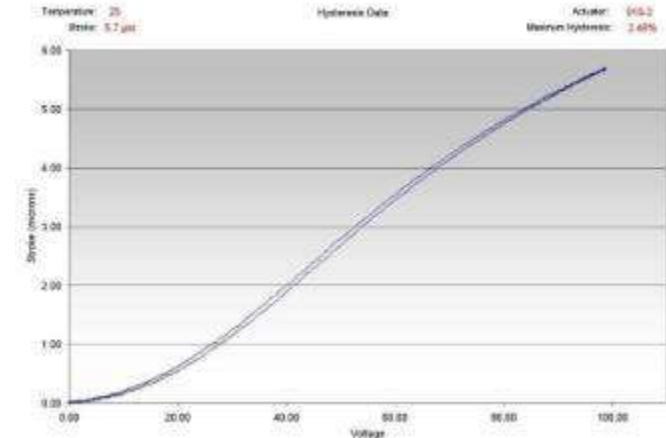
... Precision motion from precision actuators



**Dopant Tailored Response
Optimized to Application**



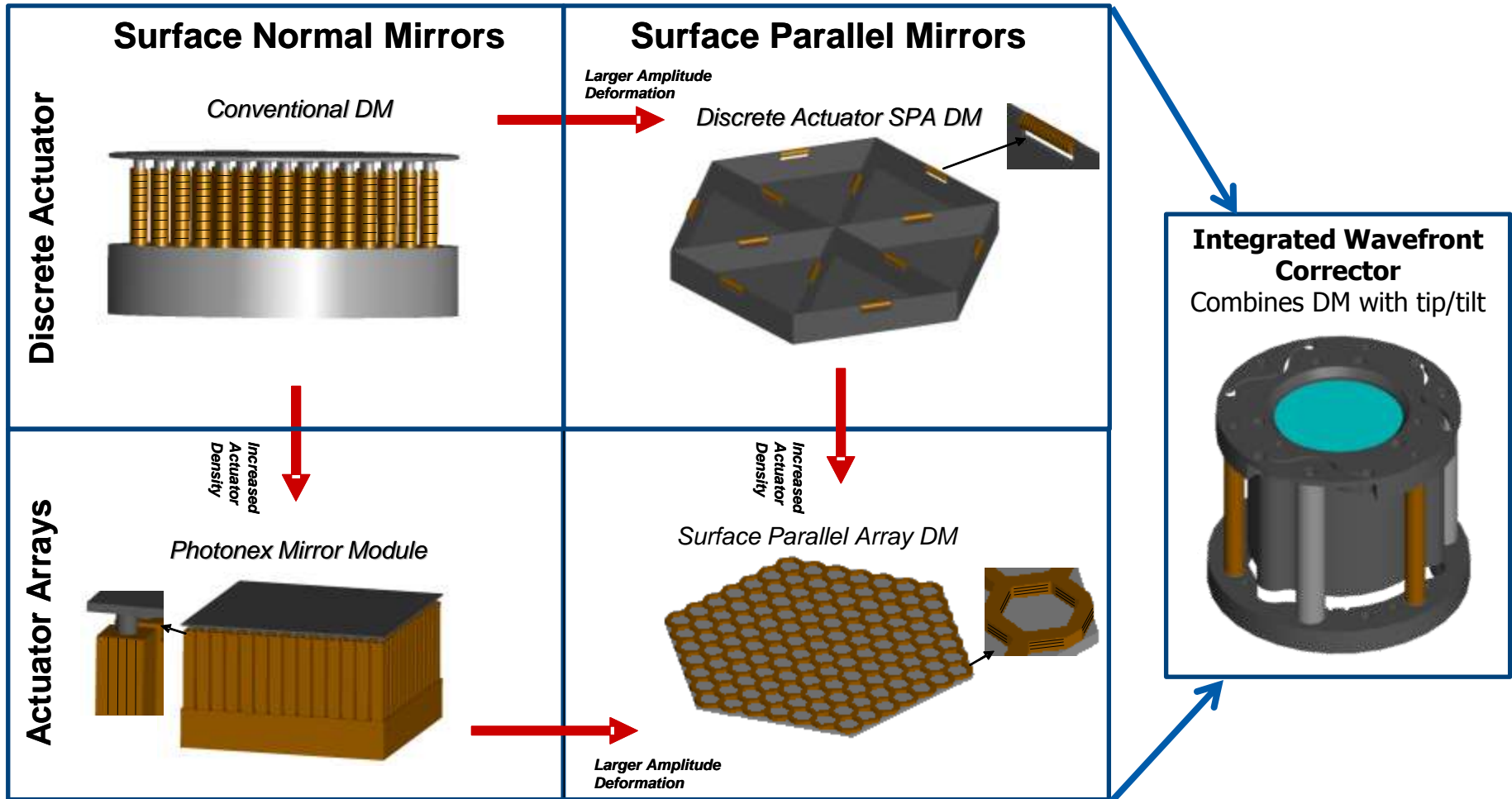
**Large Format
Multilayer Cofired Actuators**



PMN Transfer Function

- Electrostrictive Lead magnesium niobate (PMN) multilayer cofired actuators
- Exhibits little to no hysteresis, aging or creep
- Material can be tailored to optimize displacement and hysteresis over desired operating temperature range
- Fabricated for 0-100V operation
- Quadratic response (non-linear) highly linear within +/- 30V operating range
- Actuator length and diameter selected to meet stroke and force requirements

Advanced Deformable Mirror Overview

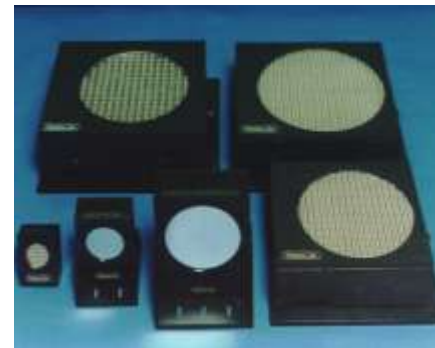
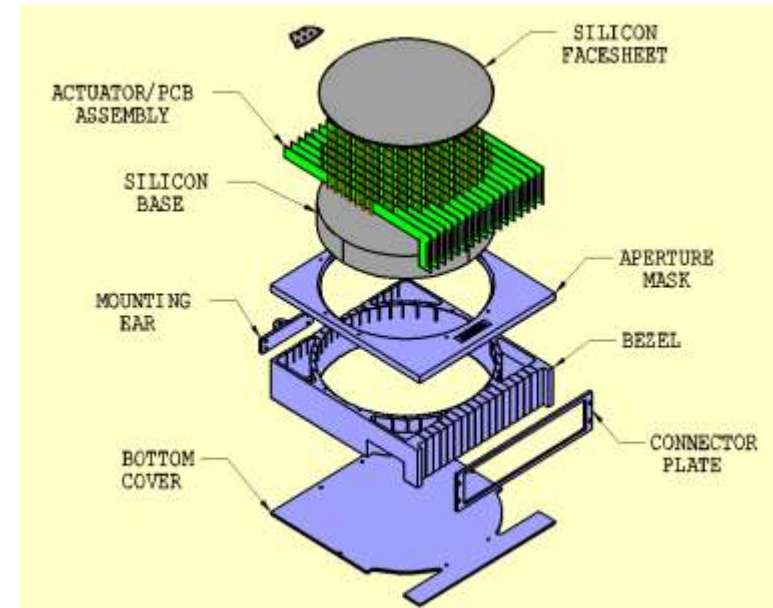


Advanced deformable mirrors utilize novel actuator technologies for precision control of optical surfaces

Traditional Deformable Mirrors

... Surface normal discrete actuators

- Surface normal actuation
 - Discrete PMN Actuators
 - Spacing of 5mm, 7mm, 9mm up to 33mm
 - Channels 37, 97, 177, 349, 577, and 941
 - Standard stroke of $4\mu\text{m}$ with custom stroke up to $22\mu\text{m}$
 - Capacitance of $2.0\mu\text{F}$
- Continuous Facesheet
 - ULE or single crystal silicon for directed energy applications
 - Zonal influence function
 - 5%-10% inter-actuator coupling
 - Inter-actuator stroke limited to $\frac{1}{2}$ free stroke
 - Apertures up to 30cm
- Rigid reaction structure
 - Same material as facesheet to minimize thermal distortions
 - Athermally bonded to mounting structure
 - Gravity sag/ attitude sensitivity $<30\text{nm}$
- High Bandwidth
 - Actuator rise time of $100\mu\text{s}$ (99% settled)
 - $>4\text{ kHz}$ small signal bandwidth
 - High authority configuration produces 8kHz full stroke bandwidth
- Optical Surface
 - $\frac{1}{4}$ wave PV, $\frac{1}{20}$ wave rms standard
 - Scratch/Dig 60/40 standard ($10/5$ achievable)
 - Surface roughness $<20\text{ \AA}$ rms standard (5 \AA rms achievable)
 - Optical coating of protected silver, aluminum, gold, or multi-layer dielectric

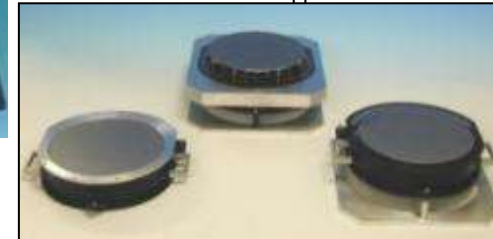


Conventional Deformable Mirrors

- Standard 7-mm Spacing
- Standard $4\text{-}\mu\text{m}$ Stroke
- 37, 97, 177, & 349 Channel Mirrors



7mm 349 Channel DM's
100KW Laser applications



ABL Deformable Mirrors

- Woofer – large amplitude stroke
- Tweeter – high spatial frequency correction

NGX Legacy: Large Scale Adaptive Optics

... Adaptive Optics Moves Out of the Laboratory

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Govt Large Telescopes

- 941-channel DMS
- 100-v Operation
- High Bandwidth



Conventional Deformable Mirrors

- Standard 7-mm Spacing
- Standard 4- μ m Stroke
- 37, 97, 177, & 349 Channel Mirrors



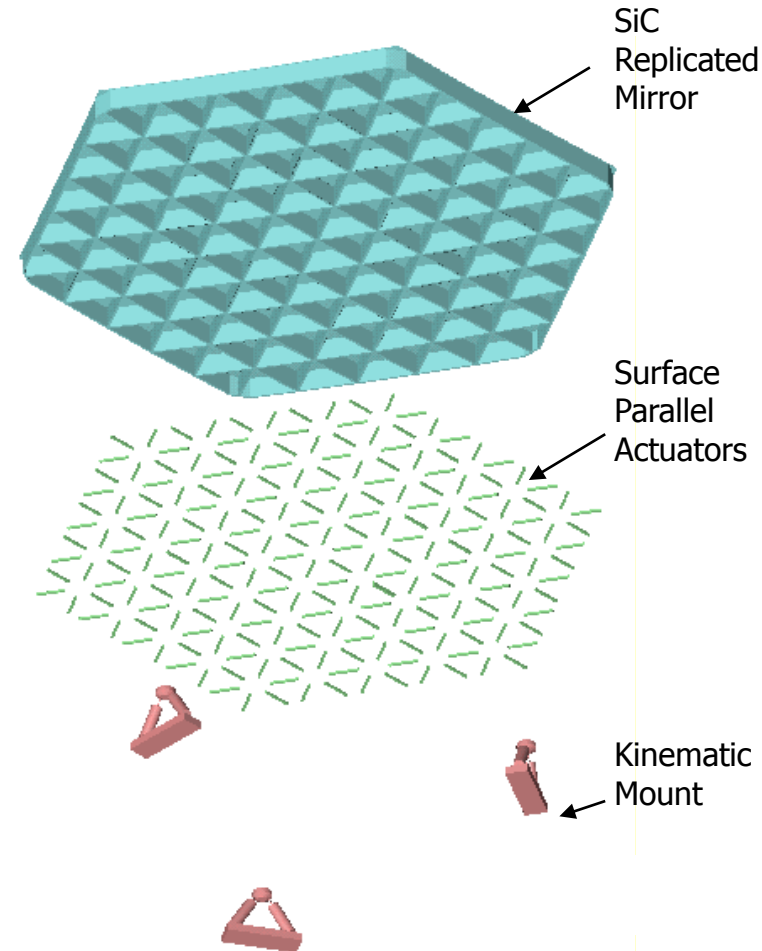
Extreme Adaptive Optics

- 577-channel DMS
- 8- μ m; 8-kHz Capability
- Tailored Spacing

Adaptive Optics Expands in the Astronomical Community with Specialty Developments in Vision, Lithography, and the Sciences

Hybrid Active SiC Mirror Technology Overview

- Surface Parallel Actuation
 - Discrete PMN actuators integrated into SiC rib structure
 - Surface parallel actuation eliminates need for reaction structure
- Lightweight SiC substrates
 - SiC provides high stiffness and dimensional stability
 - Remarkably low areal densities 10-12 kg/m²
 - Apertures up to 1.35m
- Optical Surface
 - Nanolaminate optical replication enables production on 6 week centers
 - Hybrid mirror concept works with optical polishing for applications where optical replication does not make sense
 - Optical coating of enhanced aluminum or gold
- Hybrid mirrors suitable for segmented primary, secondary, or large grazing incidence mirrors
- Replicated hybrid mirror technology compatible with SiC, graphite epoxy and glass substrates
- Active hybrid mirrors can correct for gravity, thermal errors and other errors in optical system
- Technology demonstrated to TRL-9

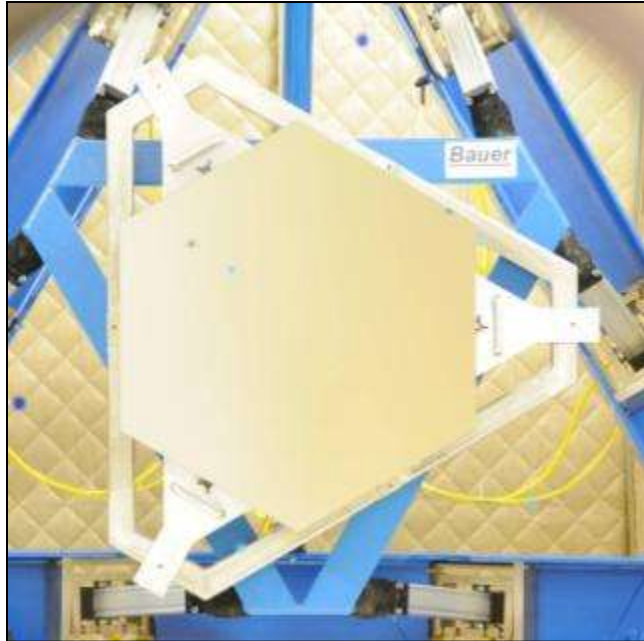


Hybrid mirrors for large lightweight segmented mirrors and production fabrication

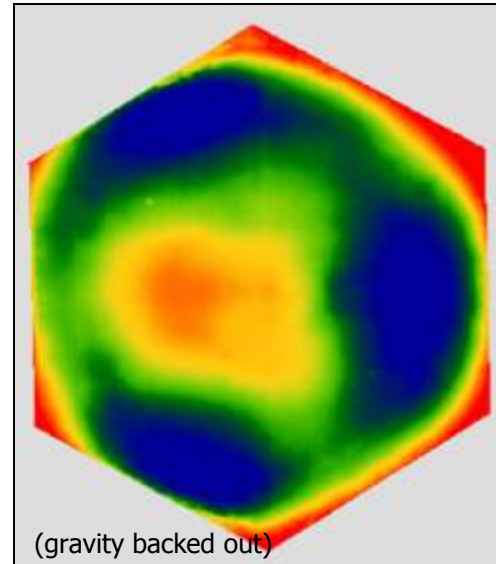
Lumens First Look Optical Figure & Correctability

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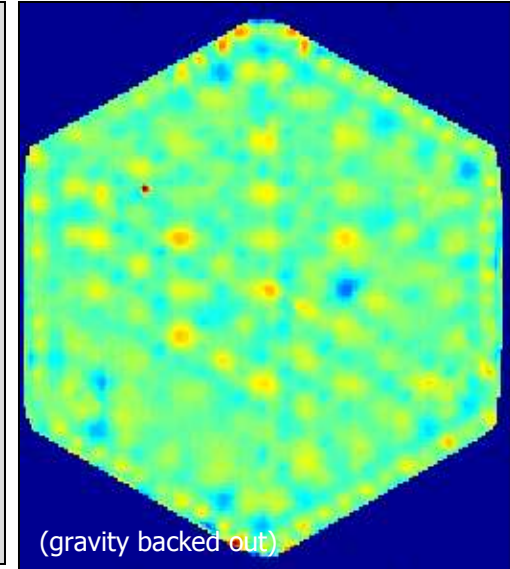
Predicted corrected optical figure 21nm RMS



Lumens Mirror First Look Metrology



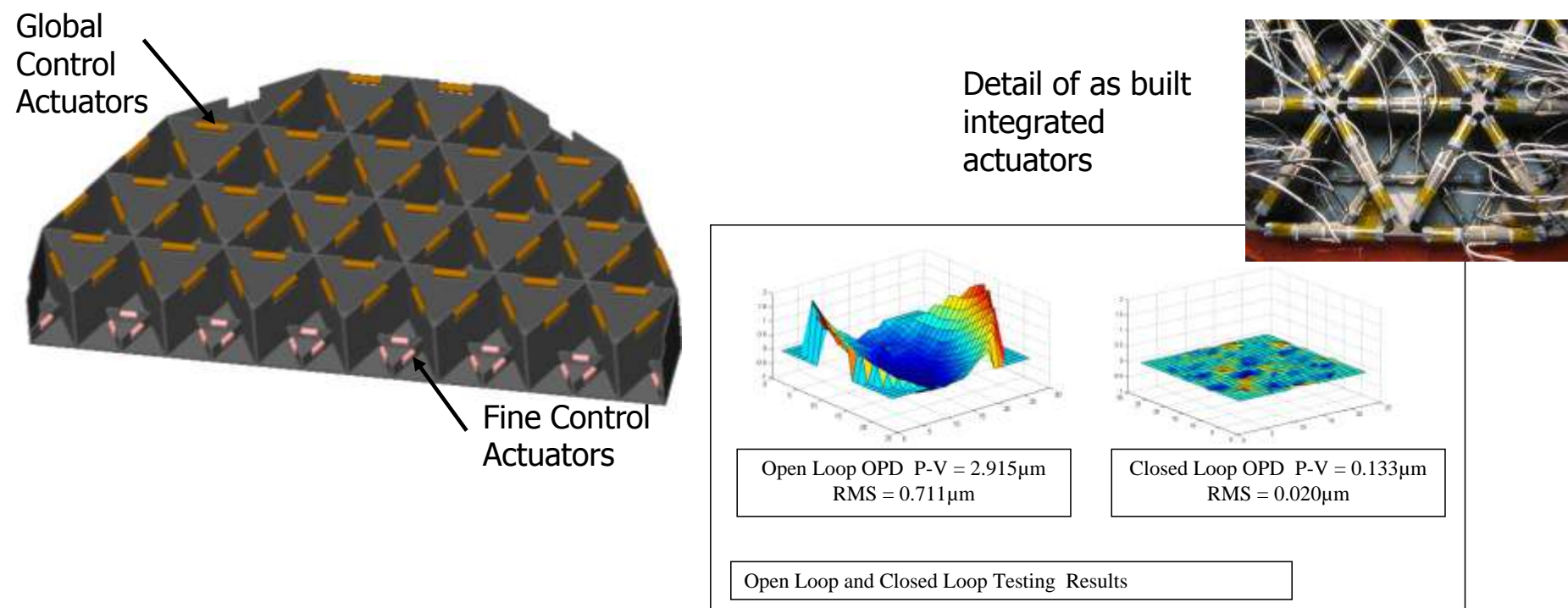
Uncorrected Statistics
SFE RMS = $0.386 \mu\text{m}$
SFE PV = $2.93 \mu\text{m}$



Corrected Statistics
SFE RMS = $0.021 \mu\text{m}$
SFE PV = $0.384 \mu\text{m}$

- First look metrology taken after NL bonding and prior to actuator integration
- Correctability predictions using 342 FEA model influence functions
- First look correctability provides indication of final mirror performance after actuator and mount integration and assembly

Combined Woofer and Tweeter Performance



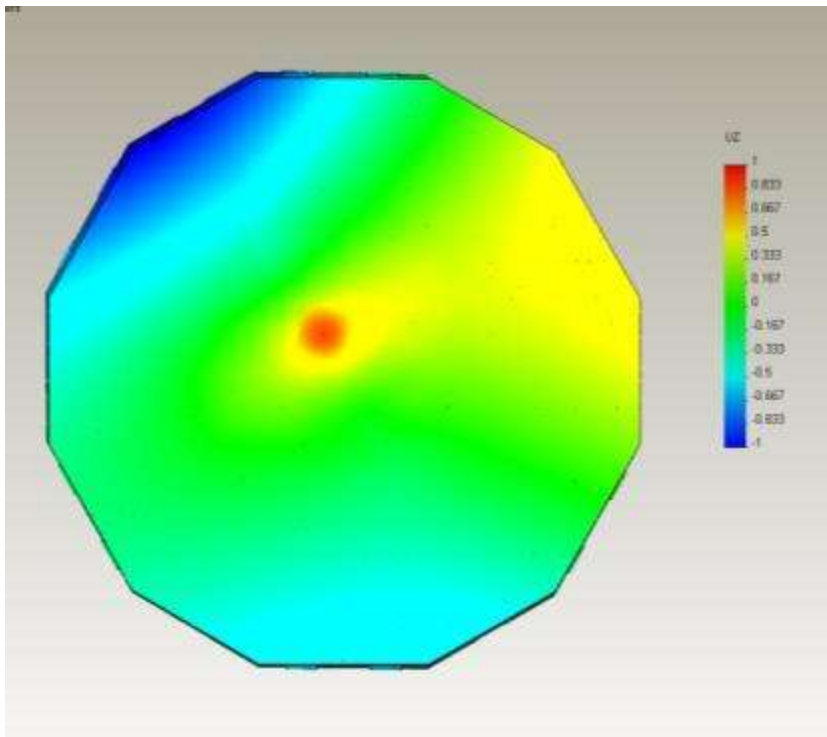
- Global Control Actuators

- Actuator is positioned into the major rib structure
- Actuator influence function extends over the entire optical surface
- Overall stroke is additive to all global actuator influence functions

- Fine Control Actuators

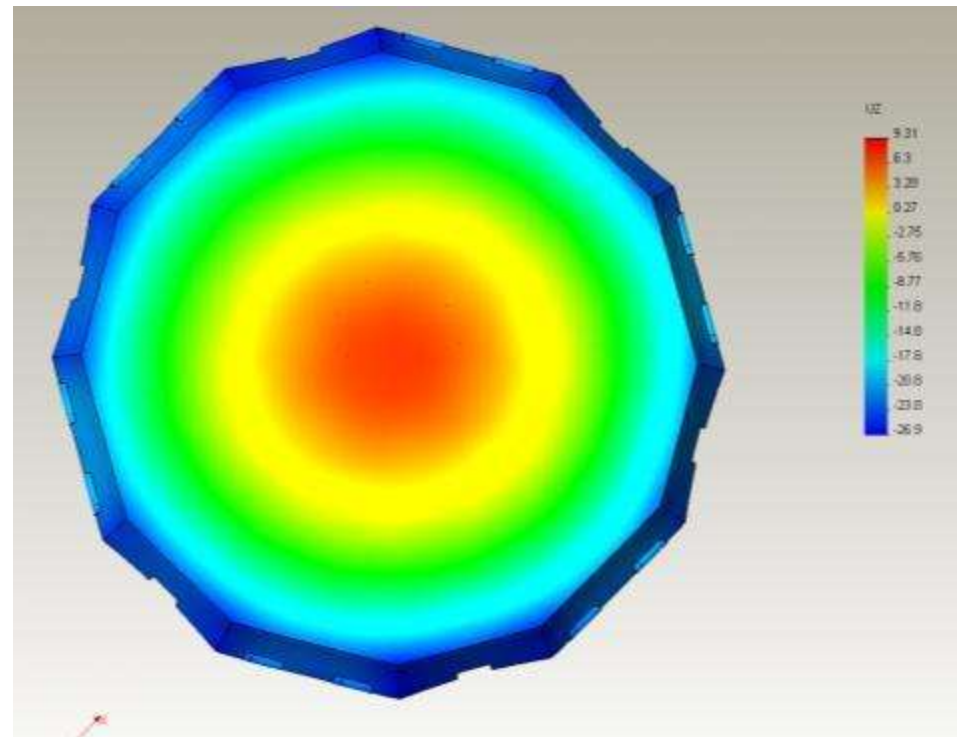
- Actuator is positioned into the short, cathedral rib structure
- Actuator influence function extends over a single iso-grid pocket
- Overall stroke is not additive, but rather couples to neighbor actuator for superior correctability

Single Global Control Actuator Activated



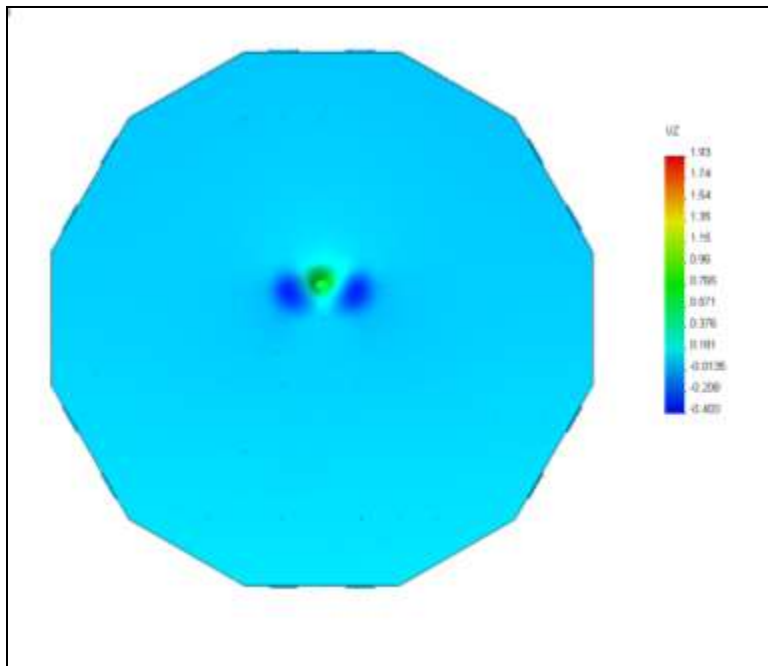
Activating a single actuator will produce local and global curvature

All Global Control Actuators Activated Produce 40 μ m Deflection



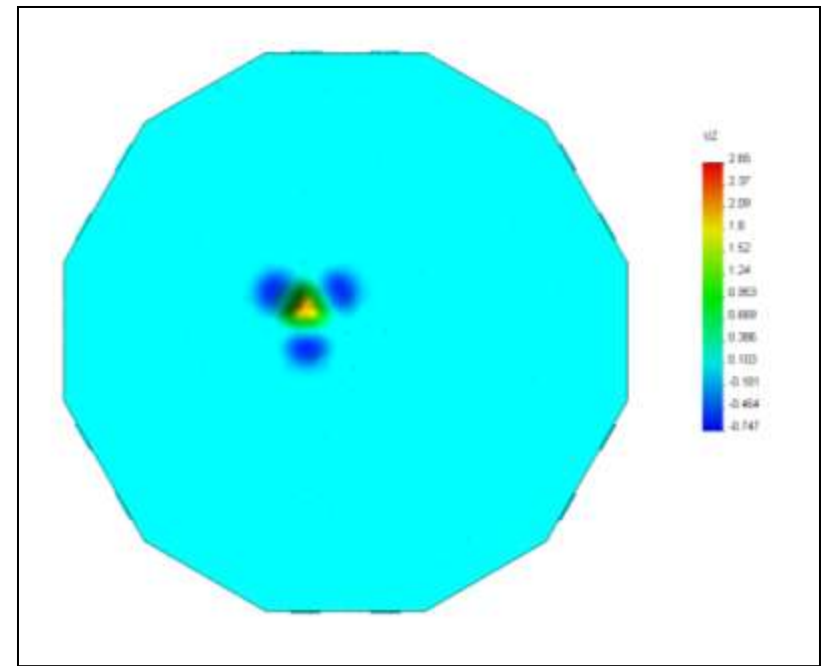
Activating all actuators will produce a Zernike defocus term

Fine Control Actuator Influence Function



Activating a single actuator will produce 4 microns of local deformation without influence of entire optical surface

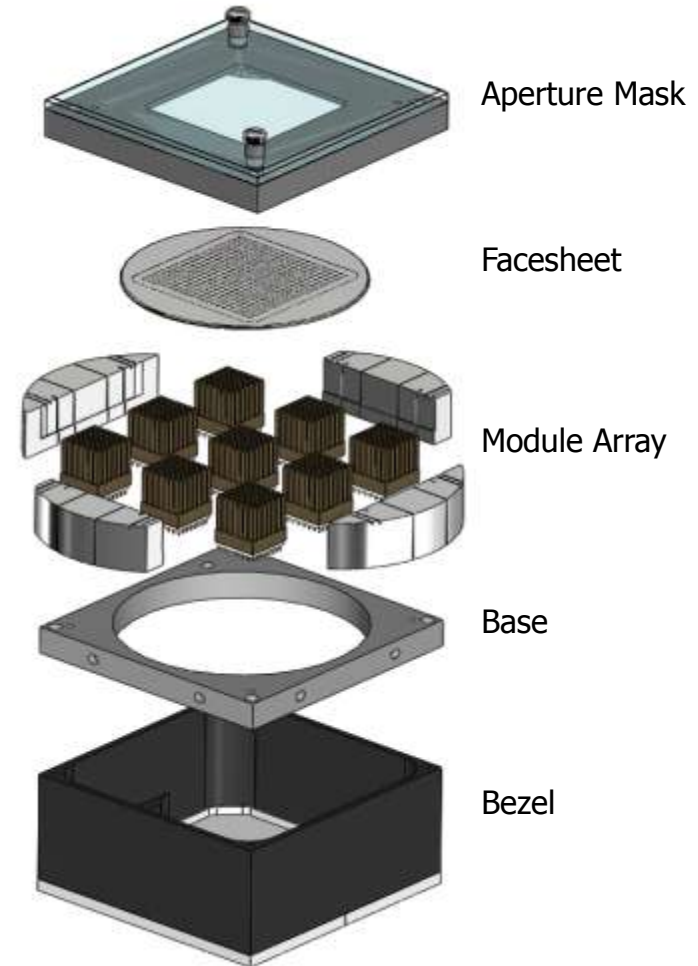
Three Fine Control Actuators Activated



Photonex Module Mirror Technology Overview

Ferroelectric Micromachined Arrays

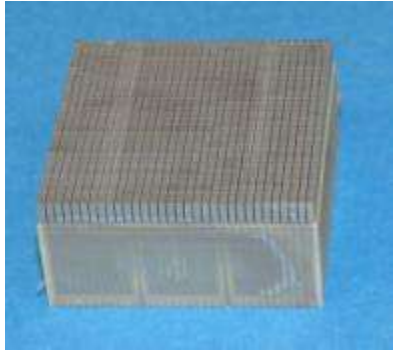
- Photonex Module Mirror Surface Normal Actuation
 - Monolithic PMN Actuator Array
 - Spacing of 1mm, 1.8mm, 2.5mm, and 7mm
 - Channels 37, 97, 196, 349, 577, 941, 1024, 1396, and 4096
 - Stroke range of $0.5\mu\text{m}$ - $2.5\mu\text{m}$ dependent upon spacing
 - Capacitance as low as 50nF
- Continuous Facesheet
 - ULE or single crystal silicon for directed energy applications
 - 5%-10% inter-actuator coupling
 - Inter-actuator stroke limited to $\frac{1}{2}$ free stroke
 - Apertures up to 150mm diameter
- Rigid reaction structure
 - Reaction structure is incorporated in the monolithic array
 - Athermally bonded to mounting structure
 - Gravity sag/ attitude sensitivity <30nm
- High Bandwidth
 - Actuator rise time of 100 μs (99% settled)
 - >8 kHz small signal bandwidth
- Optical Surface
 - <1/20 wave rms unpowered
 - Surface roughness <20 Å rms standard (5 Å rms achievable)
 - Optical coating of protected silver, aluminum, gold, or multi-layer dielectric



Photonex module mirrors for high spatial frequency correction and extreme optical quality to angstrom level

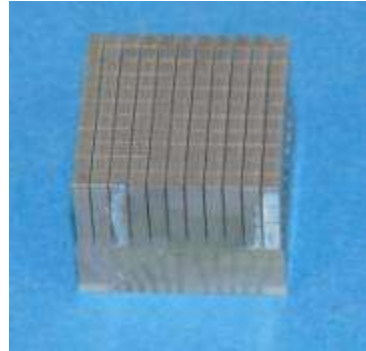
PMN Photonex Modules For High Actuator Densities

... Actuator arrays electrically addressed by PGA or BGA on back



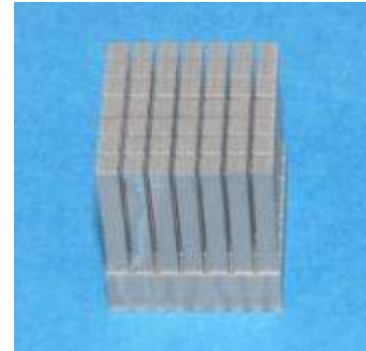
1mm Photonics Module

- 32x32 Array
- 500 nm Stroke
- 50 nF Capacitance
- Scalable to 9,216 Channels



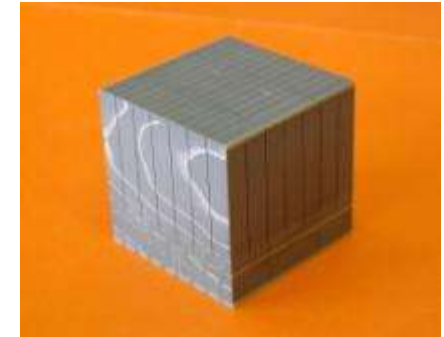
1.8 mm Photonics Module

- 11x11 Array
- 1.8 μm Stroke
- 250 nF Capacitance
- Scalable to 3419 Channels



2.5 mm Photonics Module

- 7x7 & 12x12 Arrays
- 2.5 μm Stroke
- 600 nF Capacitance
- Scalable to 1396 Channels



5 mm Photonics Module

- 7x7 Array
- 4 μm Stroke
- 6 μF Capacitance
- Scalable to 1396 Channels

2.5 mm Spacing Modular Deformable Mirrors

... Compensated imaging applications

- 2.5mm modules deliver 2.5 μ m stroke
- Large scaling using modular arrays
- Dimensionally stable to nanometer Levels
- Highly reliable with high cycle life
- Addressing via integral electrodes
- Pin grid microcircuit interconnect
- Custom interconnect to match module pitch
- Compatible with VLA & multilayer dielectric optical coatings

Number of Actuators	37, 97, 196, 349, 1396
Actuator Spacing	2.5mm
Actuator Stroke	2.5 μ m
Actuator Capacitance @ 1kHz	0.6 μ F
Operating Voltage	5 - 65 V (35V 30V)
Maximum Interactuator Stroke	1.3 μ m
Influence Function	10% at nearest neighbor
Actuator Hysteresis	< 1%
Closed Loop Frequency Response	> 2 kHz (full stroke)
Surface Figure (unpowered)	$\lambda/10$ rms
Coating	Customer Supplied



37 Channel Modular DM

- Featuring 7x7 Photonex module
- 15 mm Aperture
- Polished Figure .018 waves rms



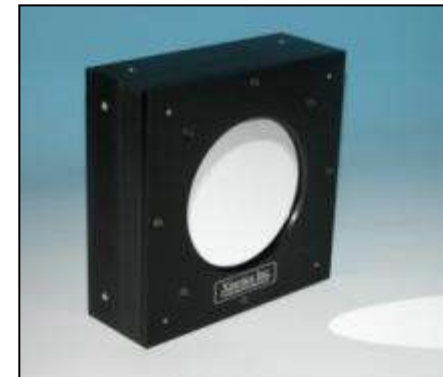
196 Channel Modular DM

- Featuring a 2x2 Array of 7x7 Modules
- 25mm Aperture



349 Channel Modular DM

- Featuring a 3x3 Array of 7x7 Modules
- 53mm Aperture



1396 Channel Modular DM

- Featuring a 6x6 Array of 7x7 Modules
- 105mm Aperture

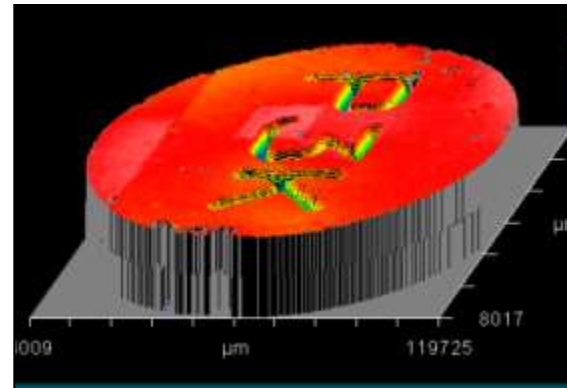
1.8mm Spacing Modular Deformable Mirrors

- 3369 Channel Deformable Mirror
 - 6x6 array of 11x11 modules
- 1.8mm Actuator Spacing
- Stroke of 1.8 microns
- High Speed Operation
- Ground Based Planetary Survey
- Mirror Built and in Acceptance Testing
- 100% Actuator Functionality



3369-ch PALM3000 Mirror

Actuator Spacing	1.8mm
Actuator Stroke	1.8 μm
Actuator Capacitance @ 1kHz	0.25 μF
Operating Voltage	5 - 65 V (35V 30V)
Maximum Interactuator Stroke	1.3 μm
Influence Function	10% at nearest neighbor
Actuator Hysteresis	< 1%
Closed Loop Frequency Response	> 4 kHz (full stroke)
Surface Figure (unpowered)	$\lambda/10$ rms
Coating	Customer Supplied

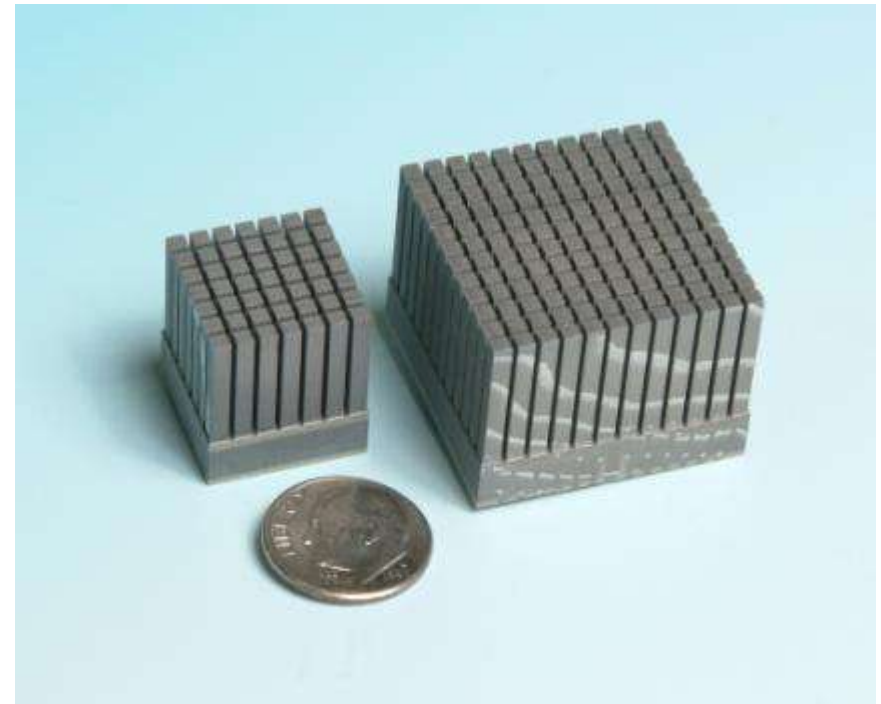
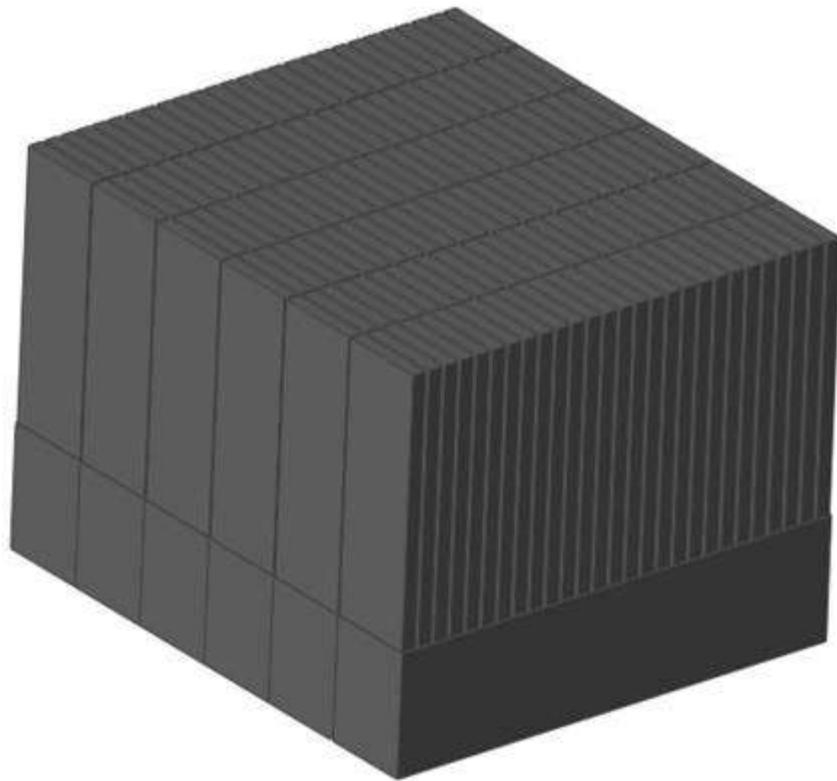


1.8mm Photonex modules provide high actuator count for high spatial and temporal frequency atmospheric compensation

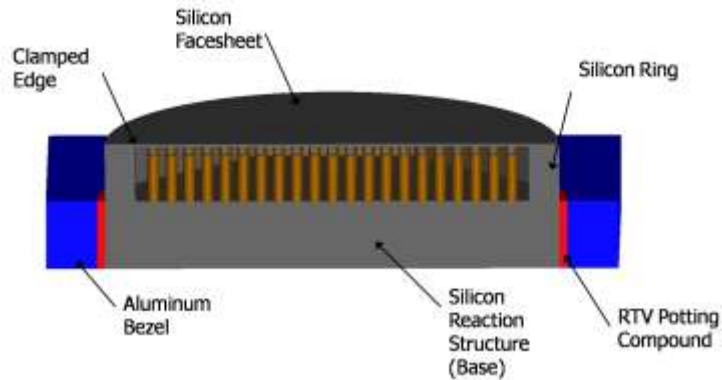
Anamorphic Photonex DM

-Solid State Laser Beam Quality Improvement

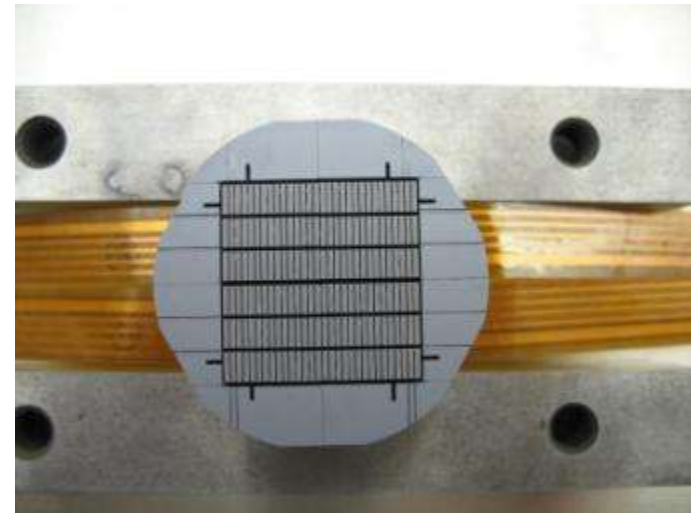
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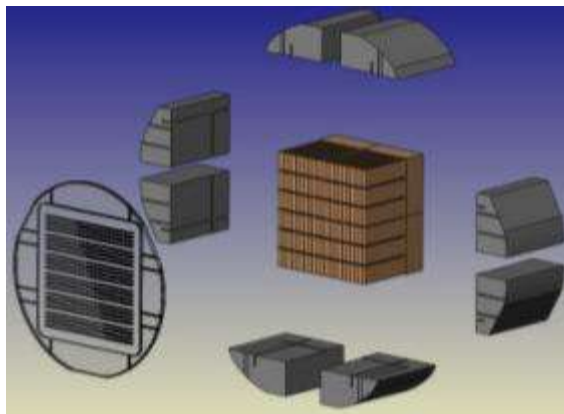
Anamorphic Photonex DM Solid State Laser Beam Cleanup



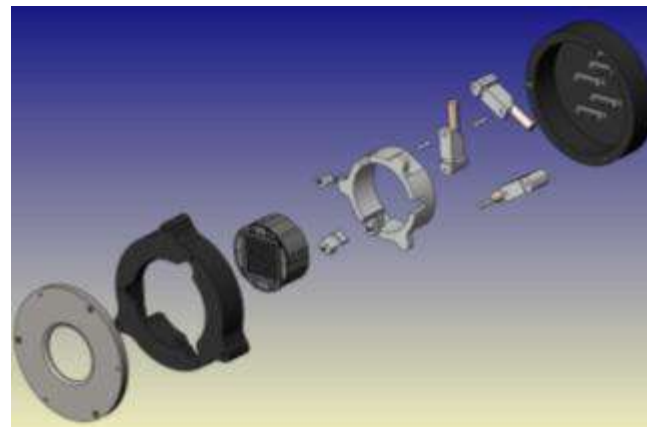
Thermally Managed DM



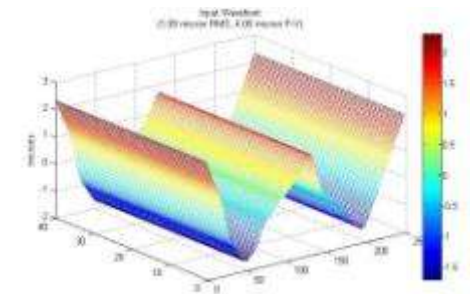
As built module



Anamorphic Photonex DM



Anamorphic DM IWC

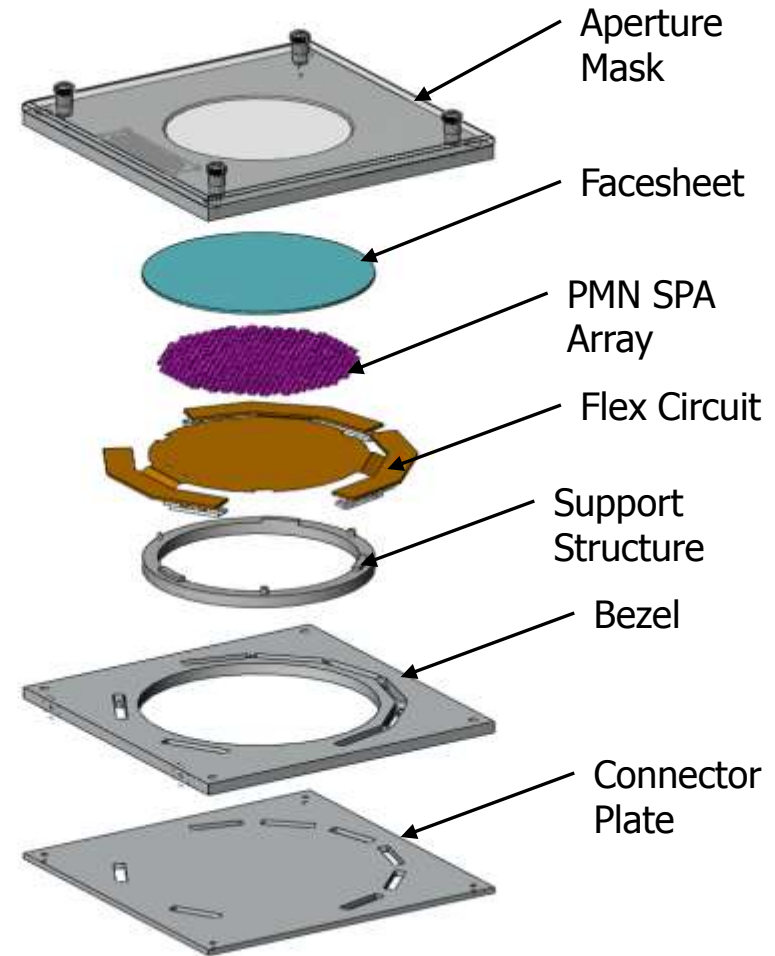


Typical SSL Wavefront

SPA (Surface Parallel Array) Deformable Mirrors

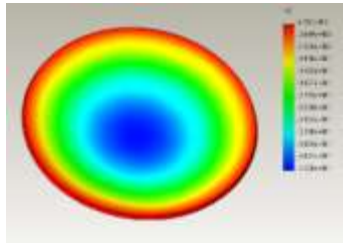
...Large amplitude & high spatial frequency correction

- Photonex Surface Parallel Actuation (SPA)
 - Monolithic Actuator Array
 - Spacing of 4mm, 6mm, and 10mm
 - Channels 37, 97, 349, and 420
 - Stroke range of up to 40 μ m
 - Capacitance as low as 100nF
- Continuous Facesheet
 - ULE or single crystal silicon for directed energy applications
 - Global influence function
 - High inter-actuator coupling
 - No inter-actuator stroke limitation
 - Apertures up to 150mm
- Rigid reaction structure
 - Reaction structure not required to achieve mirror deflection
 - Reduces weight of the deformable mirror
- High Bandwidth
 - Actuator rise time of 100 μ s (99% settled)
 - >8 kHz small signal bandwidth
- Optical Surface
 - $\frac{1}{4}$ wave rms unpowered
 - Surface roughness <5 angstroms
 - Optical coating of protected silver, aluminum, gold, or multi-layer dielectric

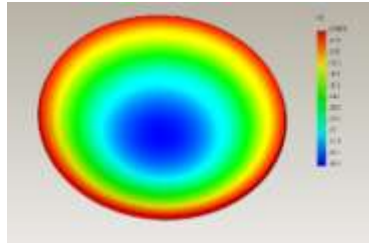


Photonex SPA mirrors combine large amplitude and high spatial frequency correction in a compact lightweight package

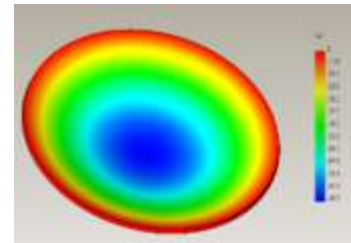
Surface Parallel Array DM's... 37 to 420 Channels



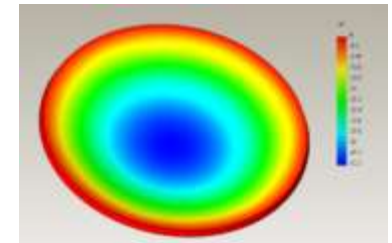
Total Deflection 44 μ m



Total Deflection 49 μ m



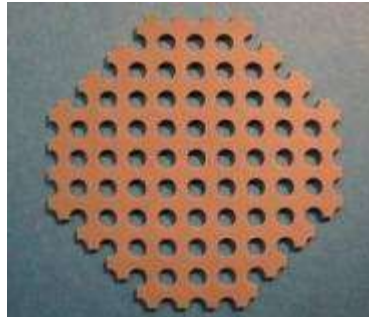
Total Deflection 90 μ m



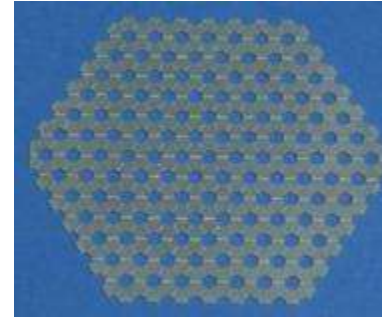
Total Deflection 51 μ m



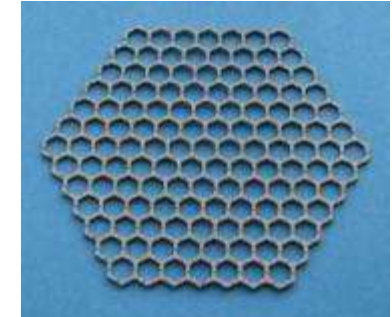
**37 Channel
10mm Spacing**



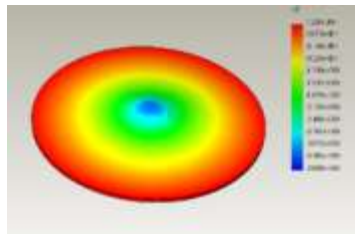
**97 Channel
4mm Spacing**



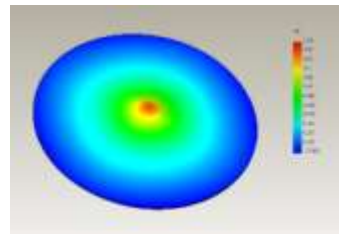
**349 Channel
4mm Spacing**



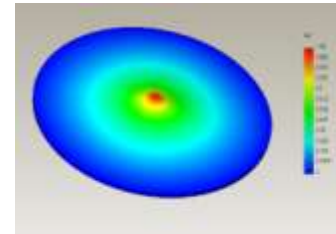
**420 Channel
4mm Spacing**



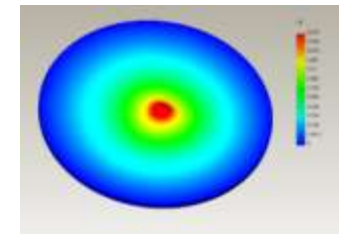
Single Actuator
Stroke 3.6 μ m



Single Actuator
Stroke 2.0 μ m



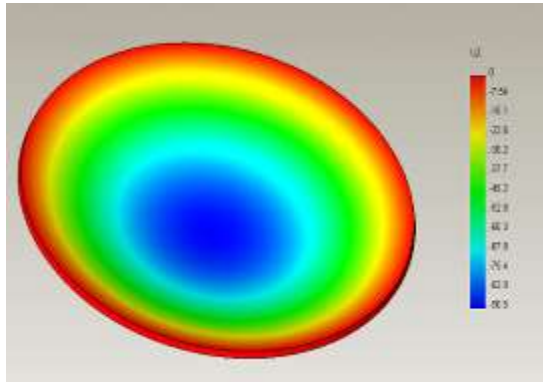
Single Actuator Stroke
1.1 μ m



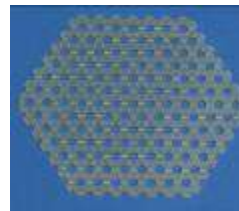
Single Actuator Stroke
550 nm

420 Channel SPA DM

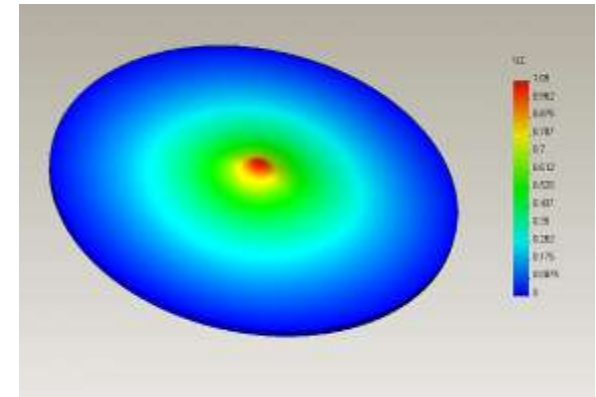
... 4mm Spacing and 100mm Aperture



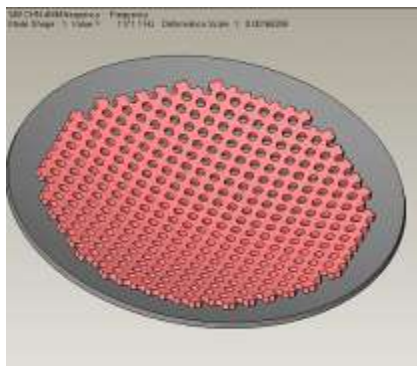
Total Available Stroke
90 μ m



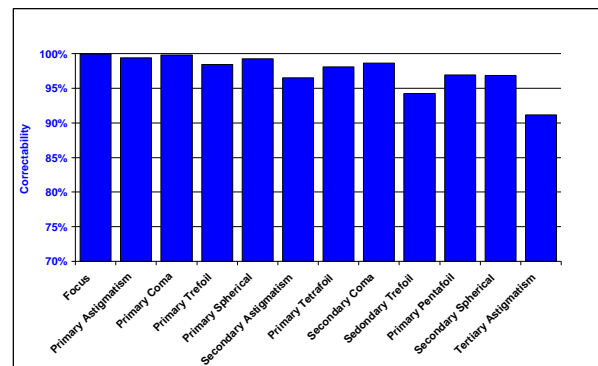
4-mm Array Spacing



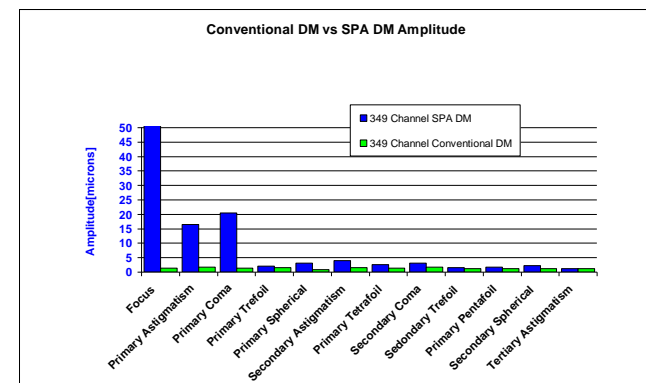
Single Actuator Stroke
1.1 μ m



First Resonant Frequency
>1.1 kHz



Zernike Correctability

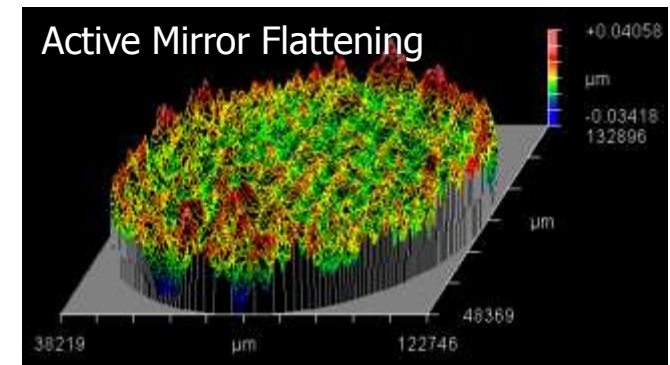
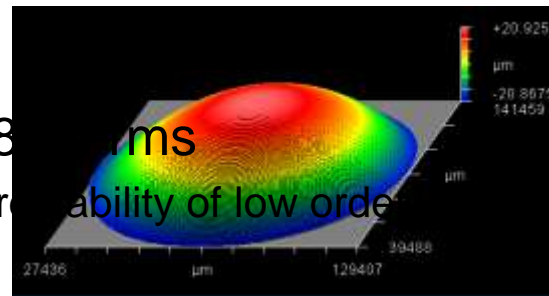
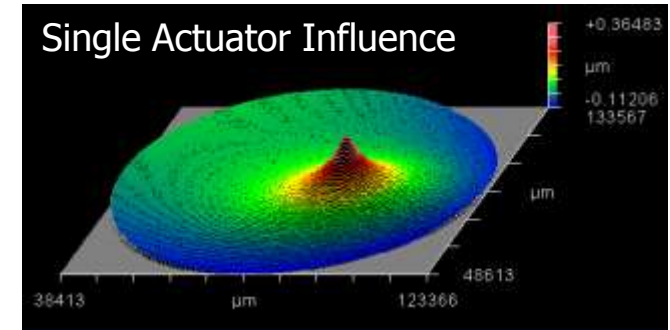


Zernike Amplitude

SPA Optical Performance

420 Channel SPA Measured DATA

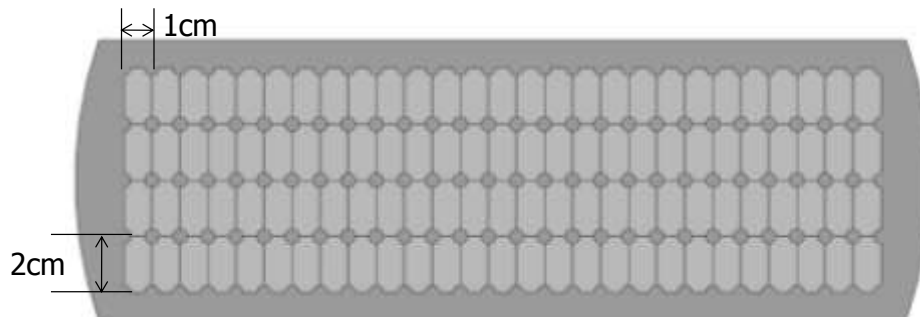
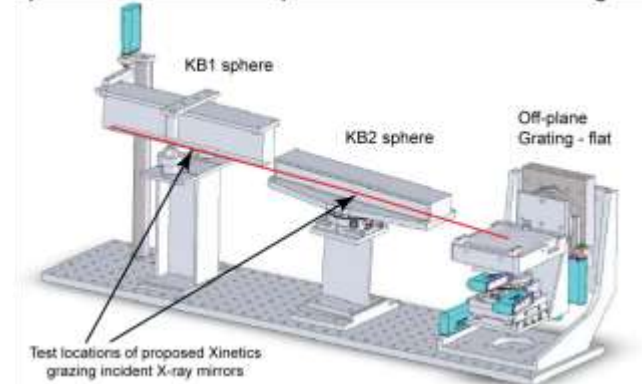
- Individual actuators addressable for high spatial frequency correction
 - 477nm single actuator stroke
- All actuators working together produce large amplitude low spatial frequency correction
 - 42 microns total stroke
- SPA DM Flattened to 8 microns
 - Obtained excellent correctionability of low order Zernike polynomials
- Excellent dimensional stability
 - The high modulus of PMN produces optimal stiffness for SPA DM
 - CTE of PMN is closely matched to silicon for ultimate thermal stability



Photonex SPA mirrors combine large amplitude and high spatial frequency correction

SPA Grazing Incidence X-Ray DM

Optics Test Chamber: Kirkpatrick-Baez Mirrors and Grating



Actuator Layout, X-ray DM

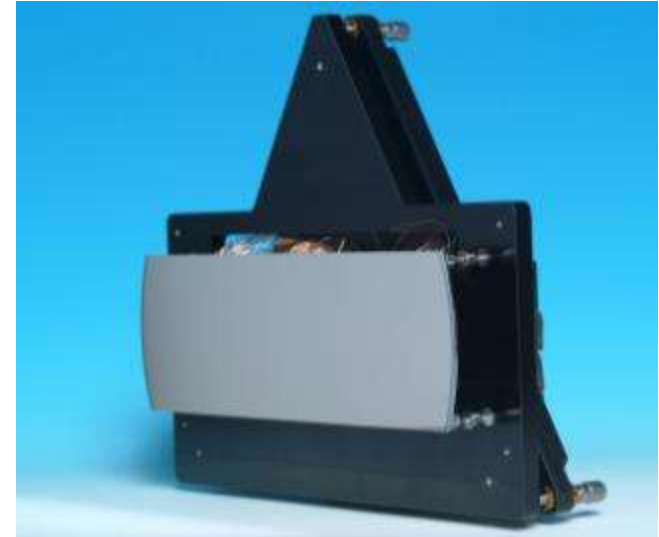
108 PMN Actuators

4 x 27 actuator grid layout

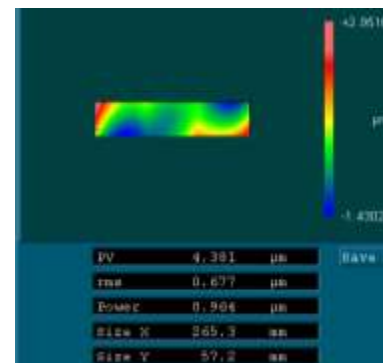
1 x 2cm, .050" thickness

10 x 30cm Silicon Facesheet

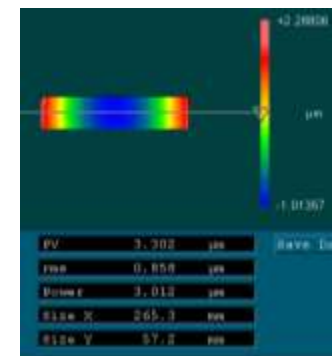
.100" thickness



Finished K-B X-ray DM



Power-off Figure

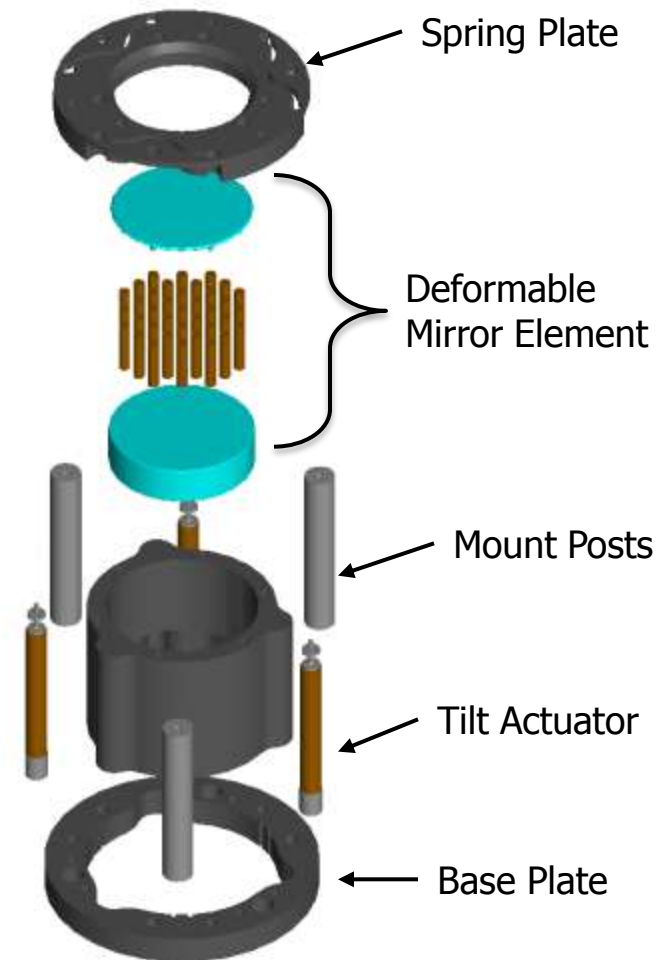


Commanded Cylinder

Integrated Wavefront Corrector Mirrors

...Combines wavefront control with beam steering functionality

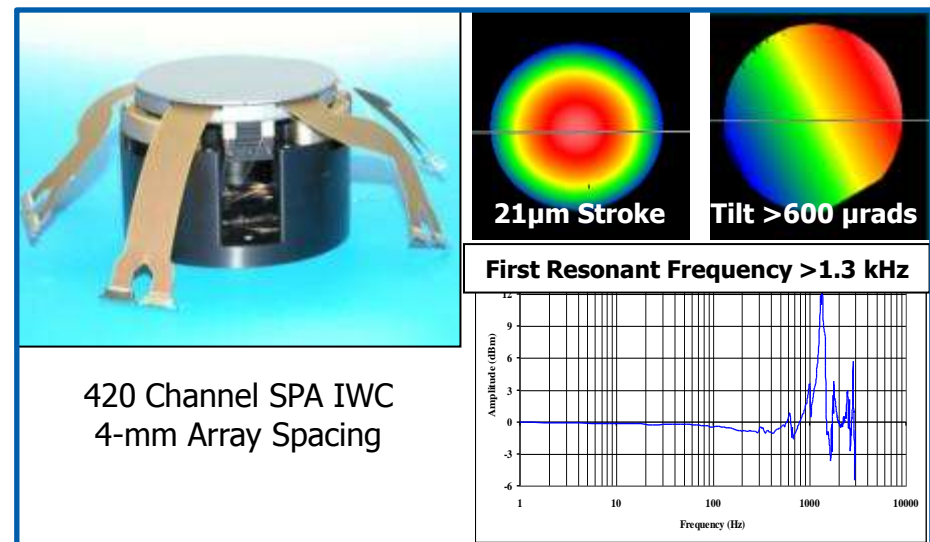
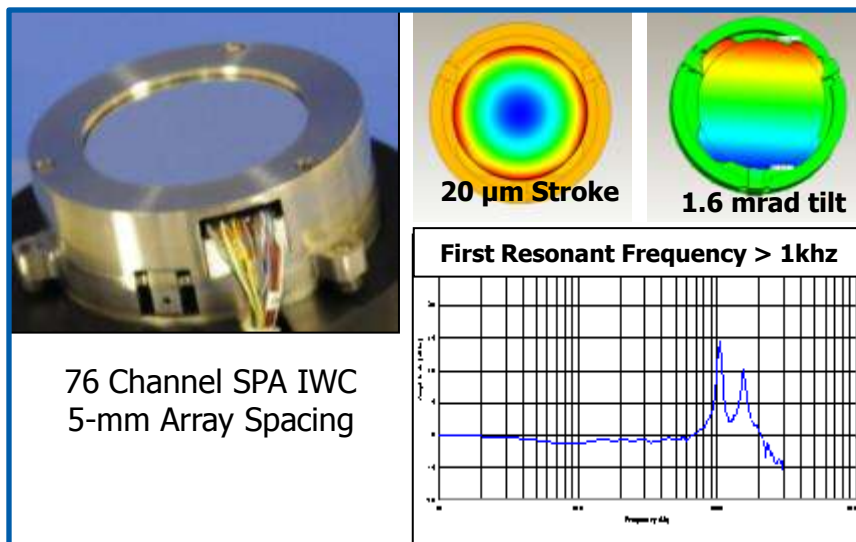
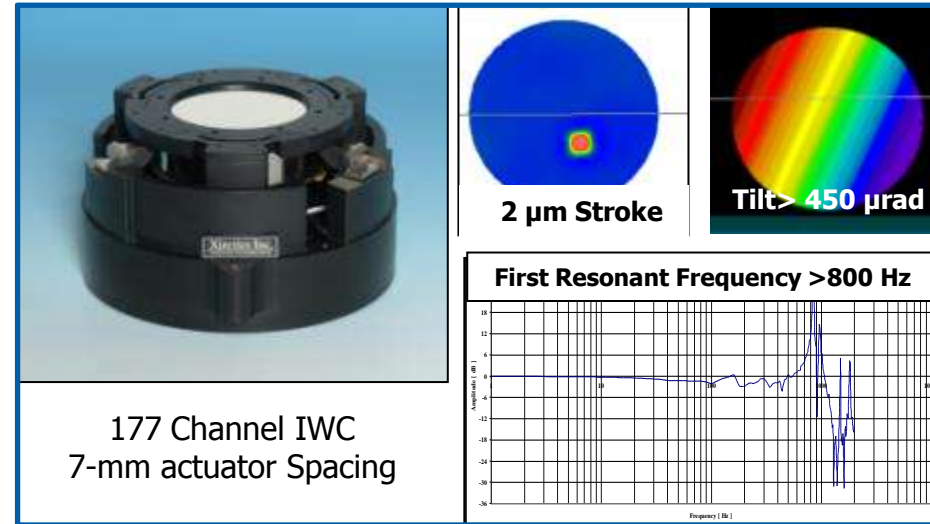
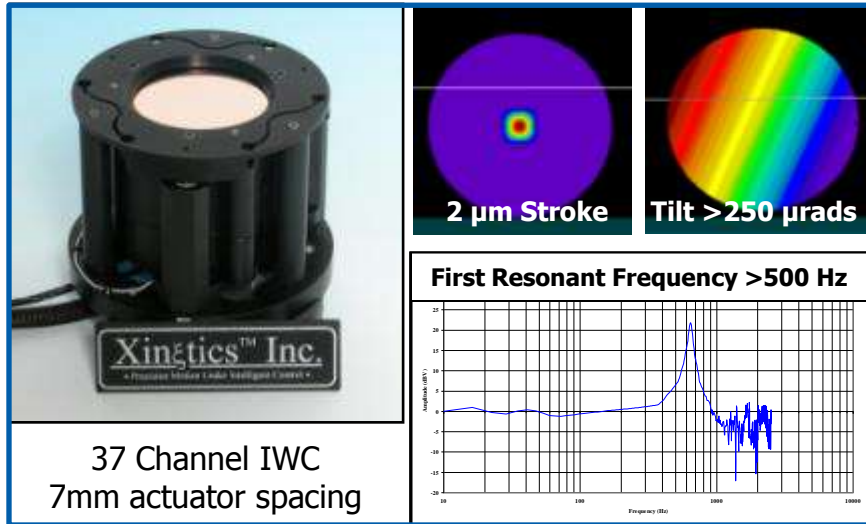
- Combine fast steering mirror (FSM) and DM function in one component
- Tilt Stage Element
 - Discrete PMN Actuators
 - Tilt range of 0.5 mrad
 - Piston of up to 22 μ m
 - High Bandwidth
 - Actuator rise time of 100 μ s (99% settled)
 - First mode resonant frequency up to 1.3 KHz
- Deformable Mirror Element
 - Works with either SNA or SPA mirrors
 - Designs produced with
 - 37 channel 7mm Conventional DM
 - 97 channel 5mm Conventional DM
 - 76 channel Photonex SPA DM
 - 420 channel Photonex SPA DM
 - 37 channel Photonex module DM



Integrated wavefront corrector mirrors enable more compact and robust adaptive optics by combining FSM and DM functions in single component

Integrated Wave Front Control Components

Examples of IWCs produced to date



Updated SPA IWC Design

- Parallel Actuator Layout Reduces Package Size

420ch IWC



76ch IWC



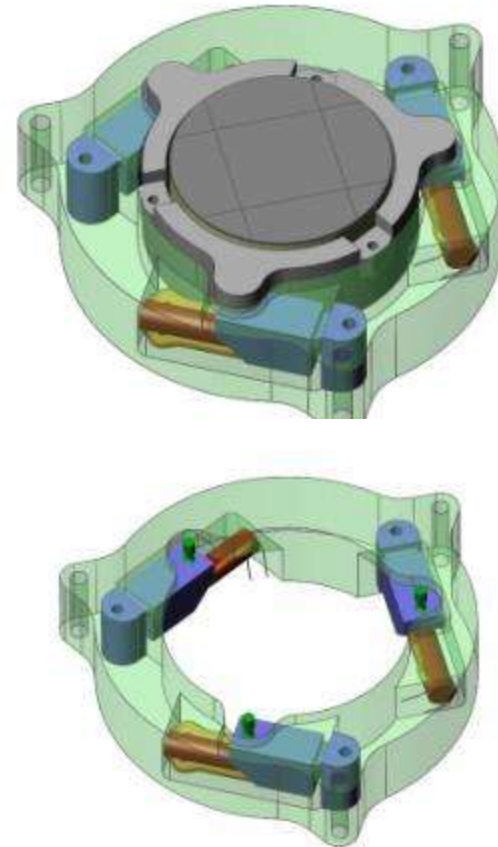
Updated DM IWC Design

- Parallel Actuator Layout Reduces Package Size

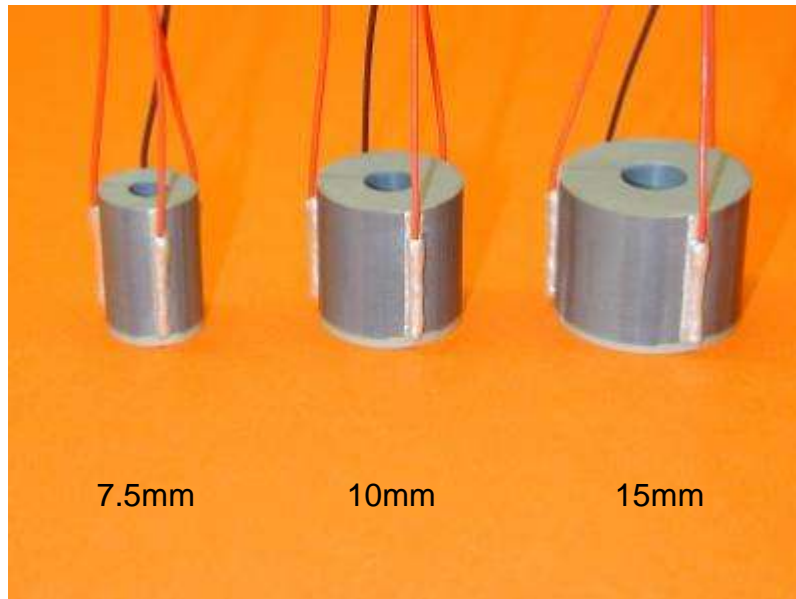
177ch Conventional DM IWC



180ch Module DM IWC

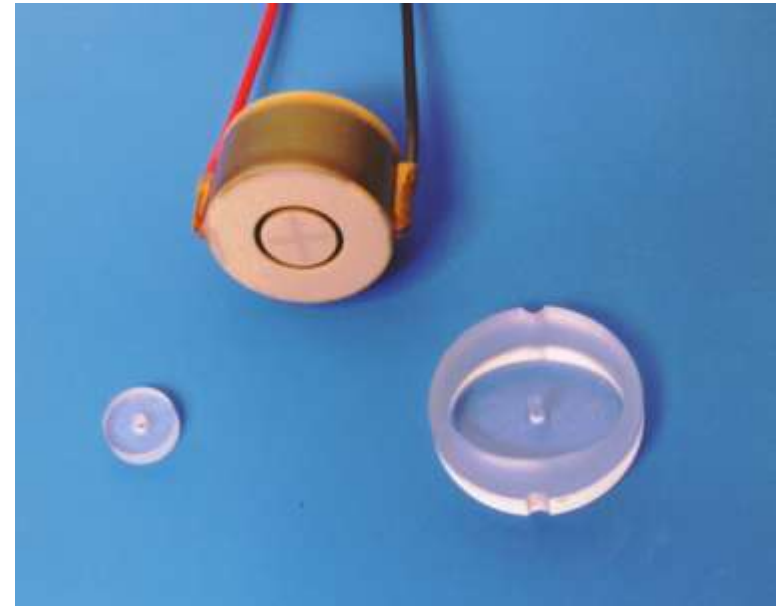


Compact Low Order Motion Control



Three degree of freedom tube actuators

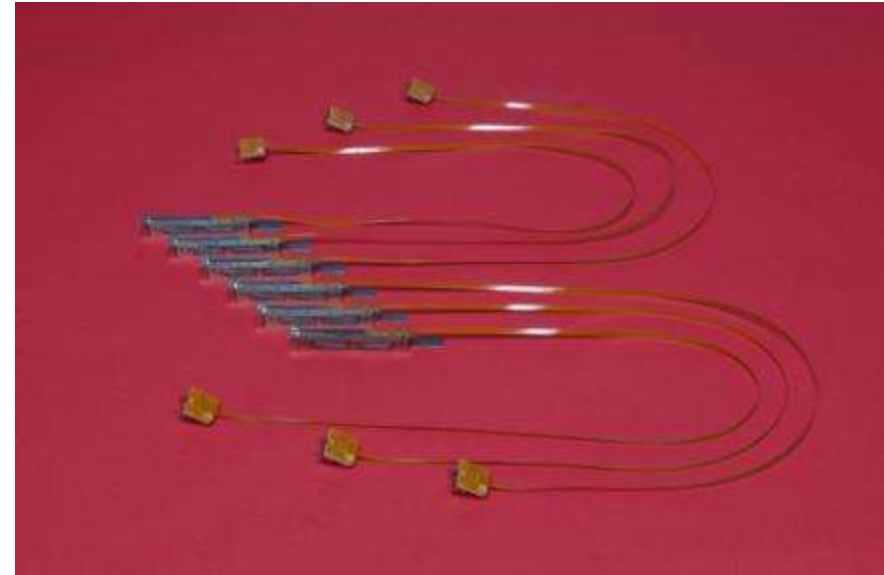
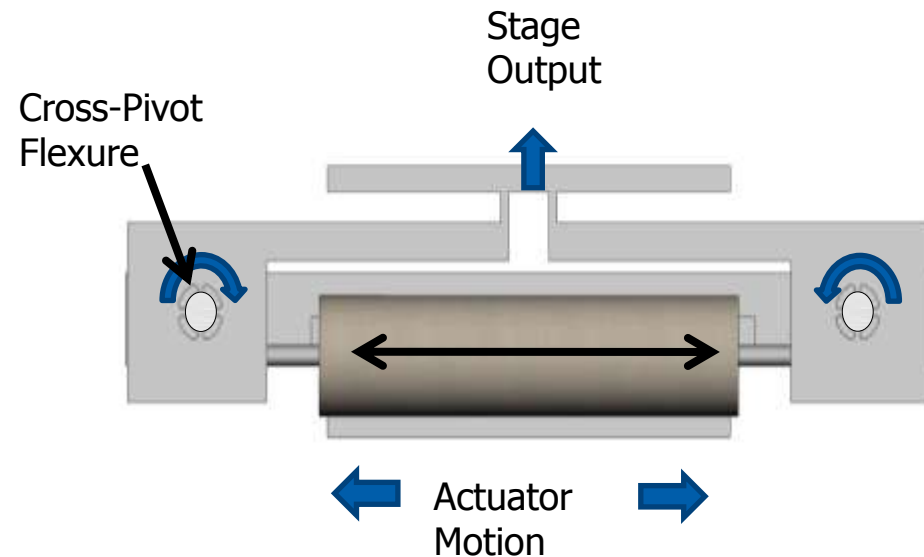
- 3 - 15mm diameter
- 0.7mradians - 2mradians
- Resonant frequency 2kHz – 40kHz



One channel DM – focus / astigmatism corrector

- 15mm Diameter
- 3 μ Deflection
- 20kHz Resonant frequency

PMN based Fiber Micro-Positioner



As built positioners

- Actuator horizontal motion translated into vertical motion
- Cross-pivot flexures machined directly into mechanism (no bushing, bearings, or preload)
- High modulus of elasticity of PMN is ideal for mechanical advantage mechanism that require high resonant frequencies
- 2nd axis stage will be attached to the output of the first stage
- 2D packing density <1cm (in x-y direction)
- 4 degrees of freedom 2 translations-2 rotations
- 40 microns of translation in X-Y
- $\pm 2\text{mRads}$ rotation

- AOA Xinetics has a unique range of deformable mirror technologies and the expertise and experience to develop custom solutions to difficult wavefront control problems
 - Actuator count from 1 to 4000+
 - Four different DM architectures
 - Extreme stability and repeatability of actuation
 - Thermally managed designs proven at 100+kW average power
 - Extensive experience with extra and intra-cavity laser beam improvement

NORTHROP GRUMMAN

